DTU Library

Leakage-free, guidance of light in hollow core optical fibers

Libori, Stig E. Barkou; Broeng, Jes; Bjarklev, Anders Overgaard

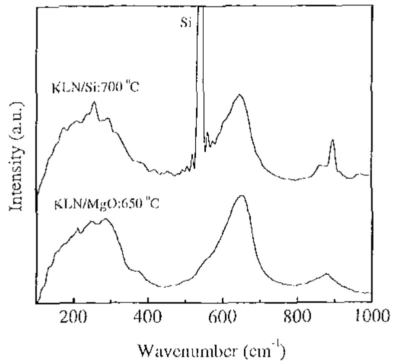
Published in:
Lasers and Electro-Optics

Link to article, DOI:
10.1109/CLEO.2000.907061

Publication date:
2000

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Libori, S. E. B., Broeng, J., & Bjarklev, A. O. (2000). Leakage-free, guidance of light in hollow core optical fibers. In *Lasers and Electro-Optics* (pp. 318-319). https://doi.org/10.1109/CLEO.2000.907061



CWK39 **Fig. 2.** Raman spectra of KLN films.

measured and the result showed that the film is highly transparent in the visible-near infrared spectral range, which is very important for the generation of blue-green lasers via SHG through near infrared laser diode pumping. The transmission rapidly decreases when the wavelength is reduced to around 320 nm, showing a direct band transition. The absorption edge of the film on MgO (~4.75 eV) extended greatly to the violet side in comparison with that of the bulk KLN crystals. The large shift of the absorption edge to the violet can be attributed to the size effect of the nano-structured film.

Light guiding measurement indicated that a 2-layer KLN/MgO film could support two TE modes and two TM modes. The refractive index of the film is 2.1443 at 632.8 nm, close to those of KLN crystal (n_o = 2.2770, n_e = 2.1630.[10]

In conclusion, we have prepared and characterized sol-gel derived KLN films deposited on Si and MgO single crystals. The results have shown that tetragonal tungsten-bronze-type KLN films could be obtained with the sol-gel process, and highly transparent and oriented KLN films were successfully deposited on MgO substrates.

1. J.J.E. Reid, "Resonantly enhanced, frequency doubling of an 820 nm GaAIAs diode laser in a potassium lithium niobate crystal," Appl. Phys. Lett. **62**, 19 (1993).
2. Y. Furukawa, S. Kakio, T. Miyai, M. Sato, H. Kitayama, Y. Urata, T. Taniuchi, T. Fukuda, "Growth and characterization of $K_3Li_2(Ta_xNb_{1-x})_5O_{15}$ crystals for blue second-harmonic-generation applications," Appl. Phys. Lett. **68**, 744 (1996).
3. Z. Chen, M. Tago, M. Adachi, A. Kawbata, "Growth and properties of tungsten-bronze ferroelectric potassium lithium niobate single crystals," Ferroelectrics **196**, 265 (1997).
4. H.R. Xia, L.J. Hu, J.Q. Wei, J.Y. Wang, Y.G. Liu, "Growth and properties of tetragonal tungsten bronze type potassium lithium niobate single crystals," Cryst. Res. & Technol. 32, 311 (1997).
5. K. Imai, M. Imaeda, S. Uda, T. Taniuchi, T. Fukuda, "Homogeneity and SHG properties of $K_3Li_{2-x}Nb_{5+x}O_{15+2x}$ single crystals grown by micro-pulling-down technique," J. Crystal Growth **177**, 79 (1997).
6. M. Ferriol, G. Foulon, A. Brenier, M.T. Cohen-Adad, G. Boulon, "Laser heated pedestal growth of pure and Nd^{3+} doped potassium niobate single-crystal fibers," J. Crystal Growth **173**, 226 (1997).
7. M. Matsukura, Z. Chen, M. Adachi, A. Kawabata, "Growth of potassium lithium niobate single-crystal fibers by the laser-heated pedestal growth method," Jpn. J. Appl. Phys. **36**, 5947 (1997).
8. G. Foulon, B. Brenier, M. Ferriol, G. Boulon, "Nonlinear laser crystal as a blue converter: laser heated pedestal growth, spectroscopic properties and second harmonic generation of pure and Nd^{3+} doped $K_3Li_{2-x}Nb_{5+x}O_{15+2x}$ single crystal fibers," J. Phys. D: Appl. Phys. **29**, 3003 (1996).
9. H.R. Xia, H. Yu, H. Yang, K.X. Wang, B.Y. Zhao, J.Q. Wei, J.Y. Wang, Y. G. Liu, "Raman and infrared reflectivity spectra of potassium lithium niobate single crystals," Phys. Rev. **B55**, 14892 (1997).
10. V.G. Dmitriev, G.G. Gurzadyan, D.N. Nikogosyan, "Handbook of Nonlinear Optical Crystals," 229 (Springer-Verlag Berlin Heidelberg, 1997).

CWK40

Leakage-free, guidance of light in hollow core optical fibers

S.E. Barkou, J. Broeng, A. Bjarklev, *Research Center COM, Technical University of Denmark, Building 348, DK-2800 Lyngby, Denmark; E-mail: seb@com.dtu.dk*

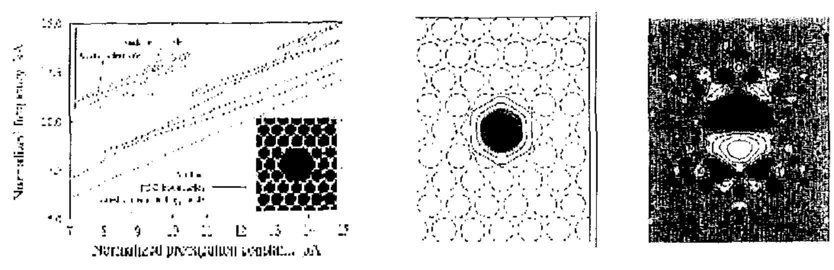
Despite their tremendous success optical fibers of today are limited by the laws of total internal reflection. During the past five years, however, it has become increasingly evident, that a new operational principle of optical fibers is possible, namely guidance due to *photonic bandgap* (PBG) effect.[1-3]

Photonic bandgaps are forbidden photon energy intervals, which may be displayed by periodic dielectric structures (*photonic crystals*), and correspond to the electronic bandgaps of semiconductor crystals. Such PBGs may exist in periodic silica/air structures.[2] While it soon became evident that it is possible to guide light in low index core regions using these fibers,[2-4] it was only recently proven that it is possible to guide light almost entirely within an air-core using PBG fibers.[5,6] In this presentation we will discuss the theory of such optical fibers and their unique properties.

The transverse design of the analyzed fiber is depicted in the inset of Fig. 1a,, where air holes are indicated in black. The central air hole corresponds to the core of the fiber, while the surrounding periodic air/silica region is the cladding structure. The fiber is assumed invariant in the longitudinal direction.

In Fig. 1 the normalised frequency, kΛ, is shown as a function of the normalised propagation constant, βΛ, where Λ is the lattice constant of the periodic cladding structure, k is the wave number and β is the propagation constant from standard optical fiber theory. All calculations were performed using a supercell plane-wave method.[7] The air-filling fraction of the cladding structure in the calculations is 70%. The lowest-frequency mode that is allowed in the cladding structure defines the cladding index of the fibre (eff. index = β/k). Index-guided modes (as for standard optical fiber) would therefore appear below the lowest-frequency cladding mode, in a plot similar to Fig. 1a. No such modes are found for the analyzed fiber. On the other hand confined modes are found within the PBGs exhibited by the cladding structure as illustrated by the second inset in Fig. 1a. This indicates that it is possible to have guided modes with a mode-index below the effective index of the cladding. The PBG regions to the left of the air-line in Fig. 1a even have a wavenumber larger than the propagation constant. It is therefore theoretically possible to obtain guided modes with all their energy in air.

Two localised modes are found for the analyzed fiber: a fundamental mode and a second order mode. Both modes are within the PBG for some frequencies, and outside the PBG for other frequencies. The modal field distribution for the fundamental mode is shown in Fig. 1b, for kΛ = 9.0 where the mode is within the PBG in Fig. 1a. It is noticed that it is indeed possible to guided light in air regions. However, when the mode exits the PBG in Fig. 1a two things happen: The mode enters a region where it may couple to cladding modes. This tendency for the mode to become leaky is further en-



CWK40 **Fig. 1.** (a) The optical fiber structure investigated (inset). A large hollow core is introduced in the central part of the fiber. The light may be guided in this region due to the periodic silica/air cladding structure. Then the guide mode lies within a photonic bandgap bandgap of the cladding structure. (b) Modal field distribution of the fundamental guided mode. It is well localised to the hollow core. Further the mode is within a PBG of Fig. 1a and is therefore strictly guided, (c) Modal field distribution of the second order guided mode. The mode is not within a PBG and is therefore leaky. A significant amount of the field is in the cladding region.

hanced, since the localised fundamental mode becomes less confined: an increasingly portion of the field is outside the hollow core as the frequency moves away from the PBG. This tendency is illustrated for the second order guided mode in Fig. 1c, which is depicted for a frequency where the guided mode is not within the PBG: The mode is not as localised to the hollow core, and is furthermore leaky.

As a consequence of the limited extent of the PBGs, the guided modes of PBG fibers will always act as bandpass filters. However, fibers where the localised modes act as the modes described above, will have a novel quality: The width and slope of the filter will depend on the actual length of the fiber. However, it should be noticed that fibers which guide light at wavelengths which are far shorter than the lattice constant of the cladding structure will typically have narrow bandgaps, and are therefore likely to have very narrow spectral ranges, where guidance is leakage free. This would therefore put severe restraints on the homogenity necessary in the final optical fiber. The fiber calculated upon here has a leakage free window in the order of 40 nm, when guidance is in the 1550 nm range.

In conclusion we have shown that it is possible to guide light leakage-free in air, in narrow spectral ranges. The analyzed fiber is not strictly single-mode, however, this may be remedied by using a fiber with a smaller air core. The importance of hollow core fibers is that they may be almost dispersionless and very linear. Furthermore, it is possible to use these fibers in sensoring schemes, or to introduce non linear gasses into the airholes to obtain new non linear fibers. This list is far from exhaustive: Possibly most important- the possibilities with these fibers are so novel, that any list will probably be far from exhaustive.

This work was supported by the Danish Technical Research Council under the THOR (Technology by Highly Oriented Research) program.

1. T.A. Birks, P.J. Roberts, P.St.J. Russell, D.M. Atkin, T.J. Shepherd, Electronics Letters, **31**,(22) 1941-3, Oct. 1995.
2. S.E. Barkou, J. Broeng, A. Bjarklev, Optics Letters, **21**(19) 1547–9, Jan 1999.
3. J.C. Knight, J. Broeng, T.A. Birks, and P.St.J. Russell. Science, vol. 282, No. 5393, 1476–1478, 1998.
4. J. Broeng, S.E. Barkou, A. Bjarklev, J.C. Knight, T.A. Birks, P.St.J. Russell. Optics Communications, **156**,(4–6) 240–4, Nov. 1998.
5. R.F. Cregan, B.J. Mangan, J.C. Knight, T.A. Knight, T.A. Birks, P.St.J. Russell, P.J. Roberts, D.C. Allan, Science **285**, 1537 (1999).
6. J. Broeng, S.E. Barkou, T. Søndergaard, A. Bjarklev, "Analysis of air-guiding photonic band gap fibers", Optics Letters, In Press.
7. R.D. Meade, A.M. Rappe, K.D. Brommer, J.D. Joannopuolos, O.L. Alerhand, Phys. Rev. B., **48**, 8834–7, 1993.

CWK41

Long distance measurement with high spatial resolution by optical frequency domain reflectometry using a frequency-shifted feedback fiber laser

M. Yoshida, K. Nakmura, Hiromasa Ito, *Research Institute of Electrical Comm., Tohoku Univ. Sendai, 980-8577, Japan; E-mail: masato@riec.tohoku.ac.jp*

Optical ranging is important in various fields, such as the characterization of an optical network, fiber optic sensors, and so on. To implement these applications, a spatial resolution better than 1 cm over an operating range of tens of kilometers is desirable. Such performance, however, has not yet been demonstrated, as far as we know. In this paper we demonstrate long distance measurement by an optical frequency domain reflectometry (OFDR) using a frequency-shifted feedback (FSF) fiber laser, and achieve a spatial resolution of 0.4 cm at an operating range of 20 km.

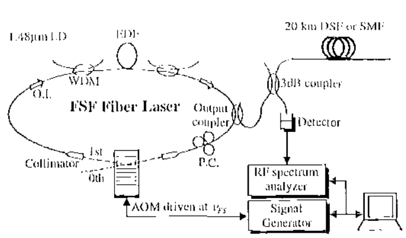
Figure 1 shows the experimental OFDR setup with the FSF fiber laser using an erbium-doped fiber as the gain medium. In this experiment, the path difference of the Michelson interferometer was set to 59 km, using 20-km dispersion shifted fiber (DSF) and single mode fiber (SMF) as test fibers to investigate the performance of long distance measurement. Fig. 2 shows the beat spectra of a self-delayed heterodyne signal for the (a) DSF and (b) SMF test fibers. Since the FSF laser output consists of a chirped frequency comb,[1] the beat frequency is given by

$$f_{Bm} = \frac{V_{FS}\,z}{\tau_{RT}\,c} - \frac{m}{\tau_{RT}} \qquad (1a)$$

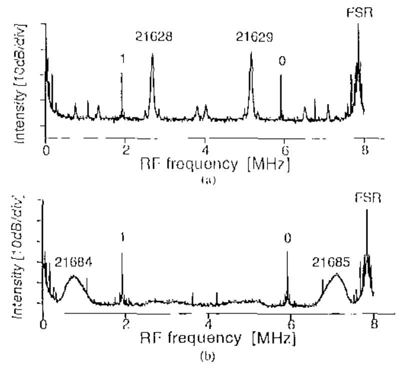
or

$$z = \frac{c}{\nu_{FS}}\,(\tau_{RT} f_{Bm} + m) \qquad (1b)$$

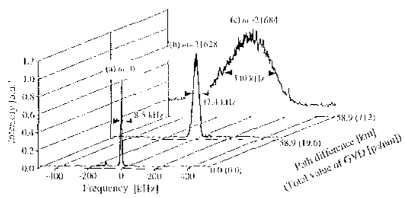
where ν_{FS} is the frequency shift per round trip (= 110 MHz), $1/\tau_{RT}$ is the cavity FSR (7.85 MHz), z is the path difference of the interferometer, and m is the "*beat order*". The beat order m is determined by the slope of the m-th order beat frequency f_{Bm} plotted against the intracavity frequency shift ν_{FS}.[2] *Thus, it is possible to measure the path difference*, z, using the higher order beat frequency observed within the cavity FSR for any path difference.



CWK41 Fig. 1. The experimental setup for long distance measurement using an FSF fiber laser, EDF: erbium doped fiber, WDM: wavelength division multiplexing coupler, PC: polarization controller, AOM: acousto-optic modulator. The driving frequency of the AOM was 110 MHz, the cavity FSR was 7.85 MHz, the output wavelength was 1.557 µm, and the frequency-chirp range was 100 GHz.



CWK41 Fig. 2. Beat spectrum of the self-delayed heterodyne signal for z = 59 km. (a) DSF and (b) SMF were used as test fibers. The lower (0^{th} and 1^{st}) and higher (>20,000th) order beat signals corresponded to the signals reflected from the two connectors of the test fiber.



CWK41 Fig. 3. Beat spectra of the (a) 0^{th} and higher order beat signals for both the (b) DSF and (c) SMF cases shown in Fig. 2. The spectrum widths (FWHM) were 8.5 kHz, 37.4 kHz, and 340 kHz, respectively.

In Fig. 2 the lower (0^{th} and 1^{st}) and higher (>20,000th) beat signals corresponded to the signals reflected from the two connectors in the test fiber. Fig. 3 shows the enlarged beat spectra of the (a) 0^{th} and higher order beat signals for both the (b) DSF (21,628th) and (c) SMF (21,684th) cases shown in Fig. 2. The spectrum widths (FWHM) of the beat signals were (a) 8.5 kHz, (b) 37.4 kHz, and (c) 340 kHz, respectively. The corresponding spatial resolutions were calculated to be 0.1 cm, 0.4 cm, and 3.9 cm using Eq. (1). The spectrum width of the 0^{th} order beat signal is determined by the frequency-chirp range of the light source (= 100 GHz), and limits the spatial resolution of this laser. The broadening of the spectrum width of the higher order beat signals is caused mainly by the effect of the GVD of the test fiber.[3] This indicates the importance of tuning the wavelength of the light source to the zero dispersion wavelength of the test fiber for a long distance measurement. When the DSF was used as the test fiber, the path difference z was measured as 58.986382 km from the fact that the 21,628th beat frequency f_{Bm} was 2.67 MHz. The ratio of the spatial resolution to the operating range $\Delta z/z$ was 2×10^{-7}, which is the best result to date for optical ranging, as far as we know.

In conclusion, we report the first OFDR demonstration of the use of a FSF fiber laser to achieve a spatial resolution of better than 1 cm over an operating range of tens of kilometers.